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MEASURING UNSTEADY PRESSURE ON ROTATING COMPRESSOR BLADES

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ABSTRACT

A program was conducted at Pratt & Whitney Aircraft under a NASA contract to establish the capability for measuring unsteady pressure on rotating compressor blades under gas turbine engine operating conditions.

Tests were run on miniature semiconductor strain gage pressure transducers mounted in several arrangements. Both surface mountings and recessed flush mountings were tested. Test parameters included mounting arrangement, blade material, temperature (20° to 150°C), local strain in the blade (up to 1680 microstrain steady and ±1000 microstrain oscillatory), acceleration normal to the transducer diaphragm (±650 G), centripetal acceleration (to 90,000 G), and pressure (to 310 kPa). Test results showed no failures of transducers or mountings and indicated an uncertainty of unsteady pressure measurement of approximately ±6 percent +0.1 kPa for a typical application. The largest sources of error were local strain in the blade (0.5 to 1.2 Pa per microstrain) and acceleration normal to the transducer diaphragm (0.33 Pa/G). The strain effect varied with transducer mounting configuration.

Finally two configurations were used on a rotating fan flutter program (on a different contract). Examples of transducer data and correction factors for this program and others are presented.

INTRODUCTION

In the world of turbine engine development there is a continuing quest for new diagnostic measurements capability. In recent years one of the objectives of this quest is measurement of unsteady pressure on the surfaces of rotating fan and low pressure compressor blades. Such measurements are especially important in developing theoretical approaches to the problems of aeroelastic flutter and acoustic noise in fans and compressors.

The measuring system which satisfies this need must meet requirements similar to those listed in Table 1. The low levels and high frequency content of the desired pressure signals implies that sensitive pressure transducers must be mounted directly on the blades. This puts the pressure transducers into a centripetal acceleration field of up to 90,000 G and a temperature environment of up to about 150°C. In addition, the

nature of the research problem requires that the installation of the transducers have a negligible effect on the aerodynamic shape and performance of the blades.

TABLE I MEASURING SYSTEM REQUIREMENTS

Unsteady Pressure Amplitude (minumum):	2 kPa peak to peak
Frequency Range:	75 to 5000 Hz
Permissible blade surface buildup: On the surface on which pressure is measured:	0.25 mm
On other blade surfaces:	0.50 mm
Blade Thickness Available	2.5 mm
Operating Temperature Range:	20 to 150^{o}C
Centripetal Acceleration, maximum:	90,000 G
Normal Acceleration, maximum:	$\pm$650 G

Most of the attempts to meet these requirements have used miniature semiconductor strain gage pressure transducers in flat configurations (References 1, 2). Others have used thin piezoelectric and film type capacitance transducers (References 3, 4). Strain gage transducer installations have been reported which operated at centripetal accelerations as high as 33,000 G without failure (Reference 1). The mounting configuration of these transducers was designed to withstand the acceleration and yet provide isolation so that the transducer is not strained as the blade distorts. Effective strain isolation is of great importance in flutter testing because of the inherent blade vibration, but definitive strain isolation data for mounting configurations that have been used are not available. In addition, only limited work has been done to investigate the effect of a steady high level of transverse acceleration on transducer calibration. Reference 5 reports such tests, but only for a low speed machine with a maximum acceleration of 1700 G. Quantitative measurements of the effect of centripetal acceleration up to 11,000 G on semiconductor strain gage pressure transducers are presented in Reference 6.

This paper describes a project designed to establish the capability for accurate measurement of unsteady pressure on rotating fan and compressor blades. This work was done by Pratt & Whitney Aircraft, Commercial Products Division, under contract to NASA Lewis Research Center. The work was done in two phases. The first phase was the design of candidate transducer mounting configurations and non-rotating testing of these configurations to determine their relative suitability. Strain sensitivity was of special concern in this phase. The second phase was rotational testing of two selected configurations from phase one. The purpose of this test was to determine the combined effect of centripetal acceleration up to 90,000 G and temperature up to 150^{o}C on the calibration of the transducers. The phase two tests included transducers mounted with

their diaphragms parallel to, and inclined seven degrees from, the plane of rotation. This was done because a transducer mounted so that its diaphragm is flush to the surface of a blade may be inclined by as much as seven degrees relative to the plane of rotation because of blade twist.

The following sections of this paper describe the transducers and mounting configurations used in this work, the procedures and equipment for both the non-rotating and the rotating tests, and the results of these tests. Also included is a discussion on the application of these results to two experimental projects, one on fan blade flutter and one on fan noise.

TRANSDUCERS AND MOUNTING CONFIGURATIONS

Miniature semiconductor strain gage pressure transducers were chosen for use on this project because they are commercially available with performance characteristics, sizes, and configurations which are generally suitable for this application. These transducers are available with an outside diameter of 2 mm and a rated full scale pressure of 170 kPa. Such a transducer can withstand overpressure of 345 kPa and yet provide a signal of 0.4 mv per kPa when excited as recommended by the manufacturer. The silicon diaphragm has high specific stiffness; this results in a natural frequency of greater than 100 kHz

TABLE II TRANSDUCER PERFORMANCE SPECIFICATIONS, UNMOUNTED

Nominal full scale pressure	172 kPa absolute
Maximum pressure	345 kPa absolute
Combined nonlinearity and hysteresis	1.7 kPa
Compensated temperature range	$27^{\circ}C$ to $150^{\circ}C$
Maximum temperature	$177^{\circ}C$
Change of sensitivity with temperature (when operated with temperature compensation module supplied)	$\pm 0.045\%$ per $^{\circ}C$
Natural frequency (approximately)	125 kHz
Acceleration sensitivity (maximum)	
(normal)	0.70 Pa/G
(transverse)	0.14 Pa/G

and remarkably low acceleration sensitivity. These transducers are available with temperature compensation and selected units are capable of operating at temperatures as high as 150°C.

Three mounting configurations were fully tested in this work; they are depicted in Figure 1 and labeled as configurations A, A', and B. Configurations A and A' are identical except that a machined recess is used in configuration A' in order to minimize the build-up of the blade surface. Using the recess, the build-up of the blade surface could be kept within the requirements listed in Table I. A flat pressure transducer, pictured in Figure 2, was used in these mounting configurations. Perforations in the shim of the transducers were specified in order to improve the strength of the bond to the blade surface. Performance specifications for the transducer are listed in Table II.

The mounting configurations shown in Figure 1 use both epoxy and RTV silicone rubber. A small epoxy bond is made between the blade surface and the perforated shim at the inboard end of the transducer assembly. The rest of the transducer assembly is cantilevered radially outward along the blade surface and floated on silicone rubber for strain isolation. Preliminary test mountings of configuration A were made with two different thicknesses (0.125 and 0.025 mm) of RTV to determine the effect of RTV thickness on strain isolation. In addition, a transducer was hard mounted with epoxy to get a baseline measurement of the strain effect. These preliminary A configuration mountings were made on Hastelloy X constant-strain-test-bars. Detailed mounting procedures and surface preparations are given in Reference 7.

TEST EQUIPMENT AND PROCEDURES

Non-Rotating Tests

Test Blades and Fixtures - In this phase of the project, the separate and combined effects of pressure, strain, temperature and vibration on the pressure transducers mounted in the various configurations were examined. For this work the transducers were mounted on blades of two different materials representing modern practice. The materials selected were titanium alloy (PWA 1202, an alloy similar to AMS 4928) and a steel alloy (consumable electrode vacuum remelt maraging steel 18 Ni-300). These materials are henceforth referred to as "titanium" or "Ti" and "steel" or "Fe".

The titanium blades were actual compressor blades available at Pratt & Whitney Aircraft. Since no steel compressor blades of approximately the same dimensions were available, steel blades were formed from flat plate twisted and bent to approximate the titanium blade shape.

Each blade was instrumented with one pressure transducer at mid chord and approximately 80 percent of blade span. A reference strain gage measuring spanwise surface strain was located just outboard of the pressure transducer and an additional reference strain gage was mounted at midchord near the root. Thermocouples were cemented to the blade adjacent to each

pressure transducer and strain gage. A pressurizing cap with a hypodermic tube termination was mounted over each pressure transducer so that the transducers could be pressurized. In order to avoid altering the strain field in the blade, the pressure cap was mounted with RTV rubber. For vibration tests, however, the caps were mounted with hard epoxy to minimize relative motion between the blade and the cap.

To provide for rapid and uniform heating to 150°C when required, the test blades were wrapped with a flexible strip heater. The time required to establish a reasonably uniform temperature of about 150°C from the root to the tip of the test blabe was about one hour.

Strain sensitivity was measured using both tensile tests and bending tests. For the tensile tests some blades were more heavily instrumented with strain gages so that strain patterns could be determined. Bending of titanium blades during tensile tests was minor, but bending of the steel blades (whose stacking line was at a considerable angle to the platform) was severe enough to produce strain reversal on one side. In the bending tests, pure transverse loads were applied to the blade root while the tip was held fixed in its bolted and cemented fixture.

For the vibration tests the blade root was clamped to a vibration table and the tip was unrestrained. A miniature accelerometer was mounted on the blades as close to the pressure measuring location as possible. Vibration tests were made at the natural frequency of the first bending mode.

<u>Non-Rotating Test Procedures</u> - For the tensile tests the range of parameters were for strain, 0 and 1000 microstrain; for temperature, 21 and 150°C; and for pressure a sequence of levels of 50, 180, 310, 180, and 50 kPa. Each test point was defined by a strain and temperature level. The sequence of pressures was to be imposed at each test point. Test points were taken in random order and a number of test points were repeated.

Prior to testing, an error analysis was made which showed that the expected uncertainty of a given measurement in terms of pressure was ±1.3 kPa. In terms of a determination of change in sensitivity this translates to an uncertainty of ±2 percent. Results from the first tensile tests verified this estimate but showed that determination of change in zero output due to strain or temperature was unacceptable due to excessive drift with time. As a result a special set of bending tests was run at only one pressure to measure the change in zero output with strain at strain levels up to 1680 microstrain. A twelve to twenty-four hour stabilization period at constant temperature preceeded these tests. As a result the short term repeatability was equivalent to the readability of the instrumentation (3 microstrain and 0.1 kPa).

Vibration test conditions are shown in Table III. The vibration tests served to determine the effect of acceleration perpendicular to the transducer diaphragm

and to establish the durability of the transducer mounting configurations in the vibration environment.

TABLE III
VIBRATION TEST CONDITIONS

	Titanium	Steel
Frequency	510 Hz	240 Hz
Peak Accel. at transducer	650 G	144 G
Peak Deflection at transducer	0.635 mm	0.635 mm
Peak Strain at transducer	100$\mu\epsilon$	100$\mu\epsilon$
Peak Root Strain	400$\mu\epsilon$	400$\mu\epsilon$

Data Reduction Procedure - Data reduction for the non-rotating tests was straightforward. The desired quantities were zero shift (change in indicated pressure output with no change in applied pressure) and transducer sensitivity (change in voltage output divided by change in applied pressure) as functions of applied strain, temperature, pressure, and vibratory acceleration. Zero shift versus strain calculations were performed only on data sets obtained within a few minutes.

Rotating Tests

Test Package - The test package used in the rotating tests is shown in Figure 3. The test package consisted of a titanium plate onto which were mounted four pressure transducers along with six strain gages and three thermocouples. This titanium plate was bolted to a spin disk for testing. The pressure transducer mounting configurations used were A and B.

One transducer in each mounting configuration was mounted in the plane of rotation and one each on a ramp at seven degrees inclination to the plane of rotation. These configurations are hereafter referred to as A,0, A,7, B,0, and B,7. The transducers were all oriented in such a way that the strain gage pattern on the diaphragm was the same and was in a position recommended by the manufacturer for minimum effects due to the centripetal acceleration. The test package was designed with a sealed cover so that pressure could be applied simultaneously to all four transducers via a stainless steel hypodermic tube connected to the inboard edge of the test package.

Spin Rig - The spin rig is shown schematically in Figure 4. It consisted of a conventional steam turbine driven spin pit assembly with a slip ring and special pressure coupler mounted above the turbine. The test package was bolted to a spin disk, with instrumentation leads and the pressurizing tube routed radially inward along the surface of the disk and then upwards through a hollow shaft to the slip ring and pressure coupler assemblies. Thermocouples were placed on the spin disk to permit measurement of the radial temperature distribution along the pressurized tube.

Figure 5 shows a schematic diagram of the pressure coupling assembly. This assembly provided a means for pressurizing the test package

while the rig was not rotating. Pressurizing was done through the pressure supply valve which was an automobile tire valve. The pressure was measured with the rotating transfer standard pressure transducer shown in Figure 5 and with an external reference pressure transducer connected to the pressure supply system. The rotating pressure transducer furnished the capability to see that no pressure was lost in the process of disconnecting the pressurizing source and to see that the pressure before and after the spin up was the same. The pressure coupler worked flawlessly throughout the program.

The temperature of the test package was controlled through the use of electrical heaters suspended from the spin pit cover.

Rotating Test Procedure - The rotating test procedure was, for the most part, dictated by the pressurizing system. Before-test estimates of the measurement uncertainties indicated an overall uncertainty of ± 2.4 kPa, with the major contributor being the uncertainty in the pressure applied to the transducer during rotation. This pressure was determined by measuring the pressure in the system at zero rotational speed and then correcting for the rotational (centripetal pumping) effects.

Corrections to the test data for centripetal pumping effects were based on the diagram and equations shown in the Appendix. The pressure ratio P3/P2 was calculated from Equation 3 assuming piecewise constant temperature. Then P3 was calculated from Equation 5. Measurements of the radial temperature distribution along the pressurizing tube indicated that the temperature was constant within a few degrees over any of the five radial segments; the error due to such a temperature gradient was less than 0.5 percent and was neglected. The estimated error in determination of P3 was ± 2.1 kPa, for the worst case.

The rotating tests provided data for the various mounting configurations as follows:

A,0 up to 75,000 G and up to 82°C
A,7 up to 55,000 G at 27°C only
B,0 up to 75,000 G at 27°C only
B,7 up to 27,000 G at 27°C only

The rotating test plan was to include centripetal acceleration up to 90,000 G and temperature to 82°C for all configurations. These parameters were actually imposed on all configurations but a series of failures prevented the obtaining of data over the full parameter range. None of these were transducer failures attributable to imposition of the test parameters.

In addition, another transducer mounting configuration was tested. This was a configuration A mounting except that no epoxy was used at the inboard end of the transducer assembly. This transducer was neither electrically connected nor pressurized; its purpose was to see if the simpler mounting would survive the environment. The test was a success.

Data Reduction Procedure - From each of the rotating test runs five end quantities were calculated after correcting the data for drift and for deviation from the standard set pressures of 7,150 and 310 kPa:

Zero shift due to rotation at 7 kPa

Zero shift due to rotation at 150 kPa

Zero shift due to rotation at 310 kPa

Sensitivity change (7-150 kPa) due to rotation

Sensitivity change (150-310 kPa) due to rotation

RESULTS AND DISCUSSION

Non-Rotating Test Results

Zero Shift - The effect of strain on zero shift as determined from the bending tests is shown in Table IV. Each data entry represents an average of 6 to 20 determinations. The mean deviation of the determinations for each test condition was less than 0.05 kPa.

TABLE IV
ZERO SHIFT DUE TO BENDING STRAIN
($Pa/\mu\epsilon$)

Configuration and Material	21°C $Pa/\mu\epsilon$	150°C $Pa/\mu\epsilon$
A,H,0.125	-0.43	
A,H,0.025	-0.51	
A,H,0.00	-8.55	
A',Fe	-2.65	-0.56
A',Ti	-1.38	-0.18
B,Fe	-1.27	-0.85
B,Ti	-1.15	-0.57

Note: Configurations A,H,X.XX denote configuration A mountings on a Hastelloy X constant-strain-test-bar. The numbers following the A,H indicate the thickness in mm of the RTV between the bar and the transducer shim.

The results presented in Table IV indicate that local strain in the blade can cause a false signal (i.e., not pressure generated) which is not readily differentiated from a pressure generated signal. This signal varies from 0.2 to more than 2 Pa per microstrain depending on configuration and temperature. The considerably greater strain sensitivity of the A',Fe compared to the A',Ti specimen is considered a geometry effect rather than a material effect. The steel blade shape was rather flat so that the machined recess had relatively deeper side walls and greater stress concentration. At 150°C, the strain sensitivity of all configurations is considerably reduced, probably due to the reduction in stiffness of RTV at elevated temperature.

A fourth configuration was included in the non-rotating tests which used a short cylindrical transducer mounted in a hole through the blade. This configuration had the lowest zero shift with strain (0.2 Pa per microstrain) of all the configurations that were tested. It was not included in the rotating tests because acceptable units could not be obtained within the scheduled time. The problem was a transducer assembly problem which has since been solved. Further details on this configuration are available in Reference 7.

The effect of temperature on zero shift requires careful discussion, since it was found to be impossible to separate unambiguously the effects of time and temperature on zero shift of the blade-mounted transducers. The most useful observation was that in no

case did sudden exposure of any specimen to a 129°C air temperature change result in zero shift rate as large as 4 kPa per minute. From this observation it was estimated that oscillatory temperature induced zero shifts in flutter studies would be negligible, less than 1 Pa (peak-to-peak) per degree C (peak-to-peak). The estimate used the fact that the thermal time constant of the transducer diaphragm is large compared to characteristic times associated with even the lowest flutter frequencies.

The effect of vibration (pure acceleration normal to the transducer diaphragm) on zero shift was deduced from careful a.c. measurements of transducer output during vibration tests on two titanium specimens at atmospheric pressure. The results are shown in Table V.

For the A' configuration the acceleration response was less than the manufacturer's specification and roughly equal to the 0.4 Pa/G value that results from a diaphragm mass-per-unit area times acceleration calculation. The measured acceleration response for the B configuration was considerably lower, which prompted a repeat measurement that confirmed the result.

The information in Table V is important because it permits calculation of acceleration induced signals which cannot in themselves be differentiated from pressure signals. The acceleration induced signals come from two sources. One is the acceleration imposed on the transducer diaphragm by the (flutter induced) vibration of the blade. The other relates to the component of the centripetal acceleration which is normal to the transducer diaphragm because of the blade twist. As the blade vibrates the local blade twist angle changes causing a variation in the normal component of the centripetal acceleration.

TABLE V
ZERO SHIFT DUE TO
VIBRATORY ACCELERATION

Configuration and Material	Zero Shift Due to Normal Acceleration Pa/G	Uncertainty Pa/G
B,Ti	0.22	0.01
A',Ti	0.34	0.01

Sensitivity Change - Calculations of transducer sensitivity (mV/kPa) were made from those data acquisition sequences in which five point pressure sequences (50, 180, 310, 180, 50 kPa) were completed within 10 to 20 minutes with no significant change in temperature. The data contained 69 such cycles including 25 repeat cycles taken at random times. Each pressure cycle permits calculation of two sensitivities (50 to 180 kPa and 180 to 310 kPa), designated low-range sensitivity and high-range sensitivity. Inspection of the raw data showed that there was no noticeable hysteresis effect; ascending sensitivities were not more than one percent different from descending sensitivities. The data from each of the 69 cycles were therefore averaged in each range to produce two sensitivity figures, low-range and high-range. Further inspection showed that the repeatabilty of sensitivity (in those cases where repeat cycles were run) was within the expected

error of the experiment (±1.4%). Therefore all repeat runs were averaged.

Examination of these data for sensitivity changes as functions of strain, temperature, pressure, and vibration revealed the following:

1. The effect of 1000 microstrain on the sensitivity of the transducers in any of the mounting configurations is zero within an experimental uncertainty of less than 0.5 percent.

2. The effect of temperature on the sensitivity of the transducers as mounted is within the transducer manufacturer's specification for thermal sensitivity change (4.5 percent per 100°C) except for the A' configuration in which case the measured sensitivity changes exceeded the manufacturer's specification by factors of 1.2 and 1.3 for the steel and titanium specimens, respectively.

3. The effects of pressure on the sensitivity of the transducers as mounted was of the order of a few percent. It should be noted that this is the percent difference between the sensitivity over the low pressure range (which is approximately the rated full scale pressure range) and the high pressure range (which is approximately from rated full scale pressure to twice rated full scale pressure). The result indicates that the user must take care to calibrate over the expected pressure range if the transducer is to be used above rated full scale pressure.

4. The effect of the test vibration levels (650 G maximum) on the sensitivity of the transducers was negligible.

Rotating Test Results

Zero Shift - Zero shift versus centripetal acceleration is presented in Figure 6. The general trend of this data shows a positive zero shift of about 0.12 Pa/G, ignoring details of configuration, orientation, temperature, pressure, and strain. The solid line in Figure 6 is the least-square-error straight line fit to the data set of 33 points (including a point at zero acceleration). The zero acceleration intercept of the straight line is close to zero (0.04 kPa). At 100,000 G the line indicates a 12 kPa zero shift.

It should be noted that zero shift as a function of centripetal acceleration does not represent an important source of error in a system designed to measure unsteady pressure on rotor blade surfaces because the acceleration at a given test point is essentially constant.

Zero shift with centripetal acceleration would be important if blade-mounted transducers were to be used to measure steady state pressure. However, the uncertainty in steady state pressure measurement will be affected not only by centripetal acceleration but also by temperature changes and the zero drift with time which was encountered in the non-rotating tests. Conservative estimates of this uncertainty are ±14 kPa for the conditions encountered in this test project. This much uncertainty, in most cases, will make it

not feasible to measure steady state pressure with blade-mounted pressure transducers.

Sensitivity Change - Sensitivity change in percent versus centripetal acceleration is presented in Figure 7. The general trend (ignoring details of configuration, orientation, and temperature) is an increase in sensitivity of about 3.5 percent per 100,000 G, an impressively small amount. The solid line in Figure 7 is the least-square-error straight line fit for the entire set of data points (including a point at zero acceleration). The zero intercept of this straight line is acceptable close to zero change in sensitivity (0.4 percent).

The standard deviation of the data set from the straight line is ±3.8 percent. On the basis of the random error analysis, a standard deviation of ±2.4 percent would have been expected. This agreement leads to the conclusion that the effect of other parameters (configuration, orientation, and temperature) in the spin tests was slight. Configuration, orientation and temperature are identified by keyed symbols in Figure 7. Inspection of these keyed symbols presents no evidence to contradict this conclusion; each set is scattered randomly around the trend line.

Post-Test Examinations - Post-test examinations were conducted including calibration of the mounted transducers and physical inspection of the mountings and leadwork on the disk. Also the B,7 transducer was carefully removed to determine that the more difficult B configuration mounting had been accomplished with no RTV extruding into the pressure port or onto the diaphragm. The entire installation was found to be in excellent condition, with no detectable migration or distortion of the RTV or epoxy. All transducers and mountings survived the test environment which included exposure to 90,000 G centripetal acceleration and temperature as high as 82°C.

Calibration History - As an overview, a calibration history of all the transducers used in the program is tabulated in Table VI. Primary calibrations were performed by the P&WA Instrumentation Standards Group; in Table VI these are marked by an asterisk. Secondary calibrations were made using the reference transducer connected to the pressure supply. The sensitivity reported is the average over the full pressure range (7 to 310 kPa).

All transducers were within specifications at room temperature when accepted for use in the program. The subsequent changes in sensitivity due to mounting were as high as 15.5 percent. However, examination of Table VI shows that there were two extreme changes, -15.5 percent and +9.1 percent; the average of the absolute value of the remaining changes was only 2.5 percent. For the mounted transducers the total further change in sensitivity during nonrotating testing was less than 2.5 percent. During the rotating tests the sensitivity of one transducer changed 19.9 percent but the average of the absolute values of the sensitivity changes was 3.5 percent with this extreme value removed. In no case did there appear

TABLE VI TRANSDUCER SENSITIVITY HISTORY

Ser. No.	Configuration	Sensitivity (mV/kPa) 21°C Unmounted *	150°C Unmounted *	21°C Mounted *	After Tensile	After Bending	After All Tests	Sensitivity Change Percent: Due to Mounting	During Test Final - Initial
				Non-rotating Tests					
98-7-62	B,Ti	0.347	0.348	0.360	0.360	0.370	0.357	+3.7	-0.8%
98-7-68	B,Fe	0.352	0.351	0.364	0.362	0.364	0.358	+3.4	-1.6%
98-7-65	A',Ti	0.415	0.420	0.431	0.434	0.426	0.420	+3.9	-2.5%
98-7-58	A',Fe	0.378	0.384	0.374	0.399	0.383	0.371	-1.1	-0.8%
				Rotating Tests, First Build					
99-4-9	A,0°	0.380	N.A.	0.376			0.386	-1.1	+2.6%
99-4-8	B,0°	0.316	N.A.	0.307			0.304	-2.8	-1.0%
99-4-15	B,7°	0.319	0.323	0.326			0.348	+2.2	+6.7%
				Rotating Tests, Second Build					
99-4-9	A,0°	0.380	N.A.	0.386			0.463	+ 1.6	+19.9%
99-4-15	B,7°	0.319	0.323	0.348			0.357	+ 9.1	+ 2.6%
99-4-3	A,7°	0.328	N.A.	0.277			0.290	-15.5	+ 4.7%

Notes: *Primary calibrations by P&WA Standards Group; others are 5-point calibrations by Development Group.

N.A. Calibration omitted

to be a progressive deterioration of a transducer during testing. These data indicate, however, that for any such applications, a calibration after transducer mounting and periodically during testing is advisable.

APPLICATION OF RESULTS

JT15D Fan Program - In the JT15D Engine Fan Noise Static Test Program at P&WA and the NASA Lewis Research Center and the JT15D Engine Fan Noise Flight Test Program at the NASA Langley Research Center, fan-blade-mounted pressure transducers were proposed for acoustic surveys. P&WA was asked to provide an assessment of accuracy of oscillatory pressure measurements of blade mounted pressure transducers for these programs, based on the results of the present test program. The assessment is summarized in Table VII. The conclusion was that when an allowance was made for ± 5 percent uncertainty in calibrations performed at frequencies up to 7500 Hz in the field, the overall error would not exceed ± 5.9 percent +0.007 kPa in the operating engine. The error includes the effects of pressure, temperature, oscillatory strain, and steady-state plus oscillatory accelerations, using configuration A including the estimated effect of a 0.25 mm RTV rubber coating on the diaphragm.

Durability for at least 15 hours up to 75,000 G was required. Experience in previous engine programs and in the present development program showed this to be realistic, the only real threat being the possibility of foreign object damage. For this reason, it was recommended that the transducer diaphragm be overcoated with about 0.025 mm thickness of RTV rubber and that one set of spare blades be instrumented.

TS22 Fan Program - Sixteen fan-blade-mounted transducers of configuration A and one of configuration B were used in the Subsonic/Transonic Stall Flutter Program at Pratt & Whitney Aircraft in 1977 under NASA Contract NAS3-20606. The TS22 fan rotor was used for which there was a library of previous flutter data available.

Operating conditions of the fan and the expected errors were essentially the same as those listed in Table VII for the JT15D application. Also, as in the case of the JT15D installation, the diaphragms of the configuration A transducers were coated with approximately 0.025 mm of RTV.

Four pressure transducers (on three blades) were selected for analysis under the present contract in order to evaluate the performance of the configuration A and B blade-mounted transducers. Each signal was analyzed at each of six fan operating points (one point in flutter and one point out of flutter at each of three operating speeds). Sufficient data were recorded to provide steady and oscillatory (amplitude and phase) strain, deflection, and acceleration values at each pressure transducer location and for each fan operating point. This made possible accurate corrections for strain and acceleration effects. Great care was taken to preserve the phase information (relative to a reference strain gage) for all sensor signals.

TABLE VII JT15D FAN BLADE-MOUNTED TRANSDUCER ERROR ESTIMATES

	Environment	
	Static	Oscillatory (20 Hz - 20 kHz)
Temperature	21 to 77°C	±0°C
Pressure	100 to 140 kPa	±7 kPa
Strain	0 to 1000	±100
Centripetal Acceleration	0 to 74,000 G	±10 G
Normal Acceleration	0 to 8000 G	±100 G

	Error Analysis					
	Configuration B on Ti Blade			Configuration A on Ti Blade		
Title	Error In Sensitivity Uncorrected Max %	Error In Sensitivity Corrected %	False* Signal kPa	Error In Sensitivity Uncorrected %	Error In Sensitivity Corrected %	False* Signal kPa
Calibration (20 - 7500 Hz)	±5	±5	-	±5	±5	-
Calibration (20 - 20,000 Hz)	±15	±15	-	±15	±15	-
Pressure Nonlinear	±0.2	±0.2	-	±0.2	±0.2	-
Temperature	±2.0	±0.8	-	±3.3	±0.5	-
Strain	±0.5	±0.5	±0.12	±0.5	±0.5	±0.05
Centripetal Acceleration	±6.0	±3.0	±0.001	±6.0	±3.0	±0.001
Normal Acceleration	-	-	±0.026	-	-	±0.054
Total Error						
RSS (20 - 7500 Hz)	±8.08	±5.91	±0.123	±8.50	±5.88	±0.074
RSS (20-20,000 Hz)	±16.28	±15.34	±0.123	±16.50	±15.31	±0.074

*Oscillatory zero shift due to oscillatory strain and acceleration

Figure 8 shows rms pressure amplitude, corrected and uncorrected, versus chordwise position for two operating points, one in flutter and one not in flutter. Corrections were small, ranging from -5 to +5 percent for oscillatory strains and -2 to +10 percent for oscillatory accelerations. Phase was taken into account in calculating the corrections. In the case of the configuration B transducer the strain and acceleration effects tended to cancel, so that the total correction was less than 3 percent. The indicated pressure fluctuation amplitude varies smoothly with chordwise position as would be expected. There is no indication that transducer mounting configuration alters the blade flutter response or the character or the pressure fluctuation in or out of flutter.

The seventeen blade-mounted transducers in the TS22 program all survived the thirty hour test program in which the maximum centripetal acceleration was 50,000 G. In this program ten hours were spent above 25,000 G, and 27 hours were spent above 20,000 G. The great majority of the transducers provided reliable oscillatory pressure measurements throughout the program.

CONCLUDING REMARKS

The capability for accurate measurement of unsteady pressure on the surface of compressor and fan blades during engine operation was established. Parameter ranges covered by this work include oscillatory pressure amplitudes as low as one kPa, absolute pressure to 310 kPa, temperature to 150°C, static strain to 1680 microstrain, oscillatory strain to ±1000 microstrain, centripetal acceleration to 90,000 G and oscillatory normal acceleration to 650 G. The blade-mounted transducers tested were the miniature semiconductor strain gage type with natural frequencies above 100 kHz. Diaphragm sensing area was one millimeter in diameter.

The error in measurement of unsteady pressure with blade-mounted transducers in a typical application is about ±6 percent (due to uncertainty in calibration and rotational effects on sensitivity), plus 0.1 kPa which represents extraneous signals due to oscillatory acceleration and strain. Use of the same blade-mounted transducers to measure steady state pressure would probably not be feasible; errors of the order of ±14 kPa were indicated by the results of the present work.

Different mounting configurations were developed and tested. These have significant differences in the amount of build-up of the blade surface and the measured sensitivity to local strain in the blade. They also present different requirements for machining of the blade to accommodate the mounting. Choice of one mounting over the other requires a judgment as to the relative importance of these factors in the particular application.

The blade-mounted transducers were found to be sufficiently durable to withstand the environment imposed by such testing. However, sufficient sensitivity changes were encountered during mounting and testing that calibration after mounting and periodically during testing is advisable.

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5. Sexton, M. R., O'Brien, W. F., and Moses, H.L.: Pressure Measurements on Rotating Blades of an Axial Flow Compressor. ASME Paper No. 73-GT-79, 1973.

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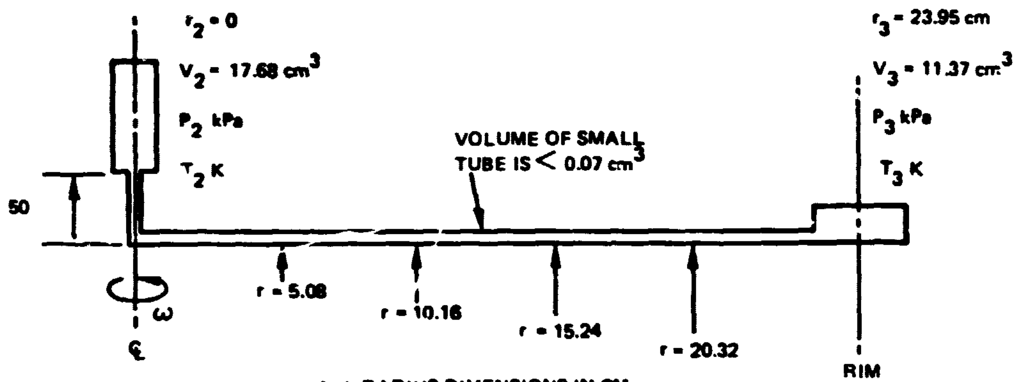
APPENDIX - PRESSURE RELATIONSHIPS IN THE ROTATING SYSTEM



ALL RADIUS DIMENSIONS IN CM

THERMOCOUPLE LOCATIONS

At $\omega = 0$, $P_{20} = P_{30}$ = pressure measured with stationary reference.
At $\omega \neq 0$, Newton's Laws require that, in the small tube, $AdP = \rho\ Adr\ \omega^2 r/G$ or

$$dP/dr = P\omega^2 r/GRT \tag{1}$$

Which integrates to

$$P_3/P_2 = \exp\left[(\omega^2/GR)\int_{r_2}^{r_3} (r/T)dr\right] \tag{2}$$

or, if T = constant from axis to rim,

$$P_3/P_2 = \exp\left[\omega^2 r_3^2 / 2GRT\right] \tag{3}$$

Also, from conservation of mass, if the volume of the small tube is negligible, then for any temperature distributions,

$$P_{20} V_2 + P_{30} V_3 = P_2 V_2 + P_3 V_3 \tag{4}$$

or

$$P_3 = P_{20}\left(\frac{T_3}{T_{20}}\right)\left[\frac{1 + (T_{20}/T_{30})(V_3/V_2)}{(P_2/P_3)(T_3/T_2) + (V_3/V_2)}\right] \tag{5}$$

where P_2/P_3 is determined from Equation (2) for any known temperature distribution or from Equation (3) if temperature is constant from axis to rim.

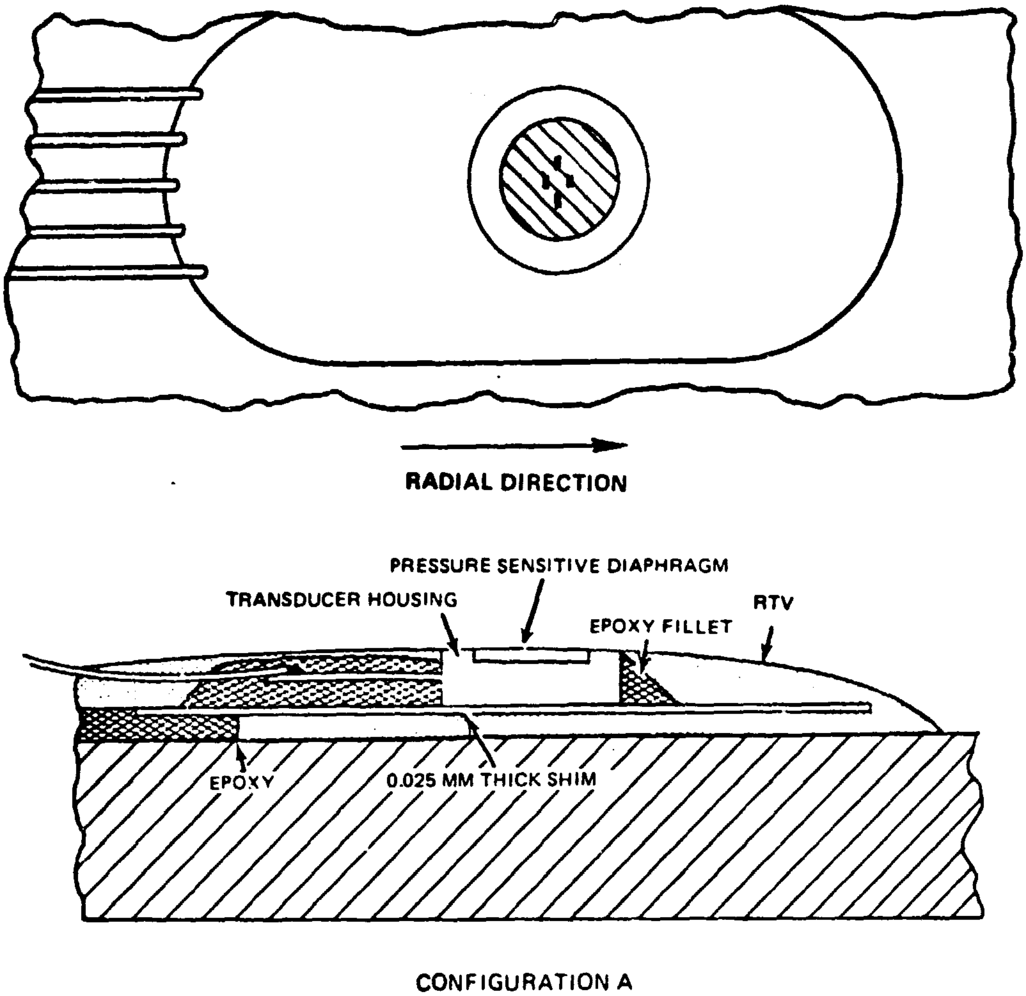
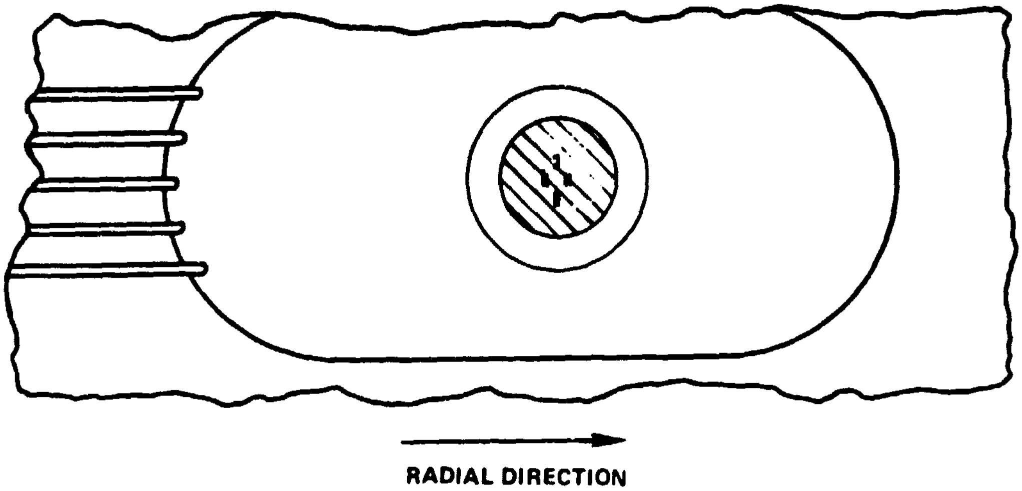
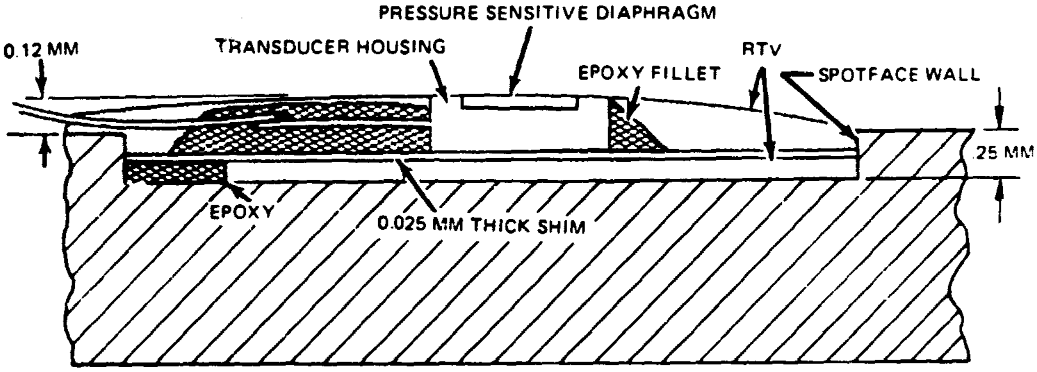


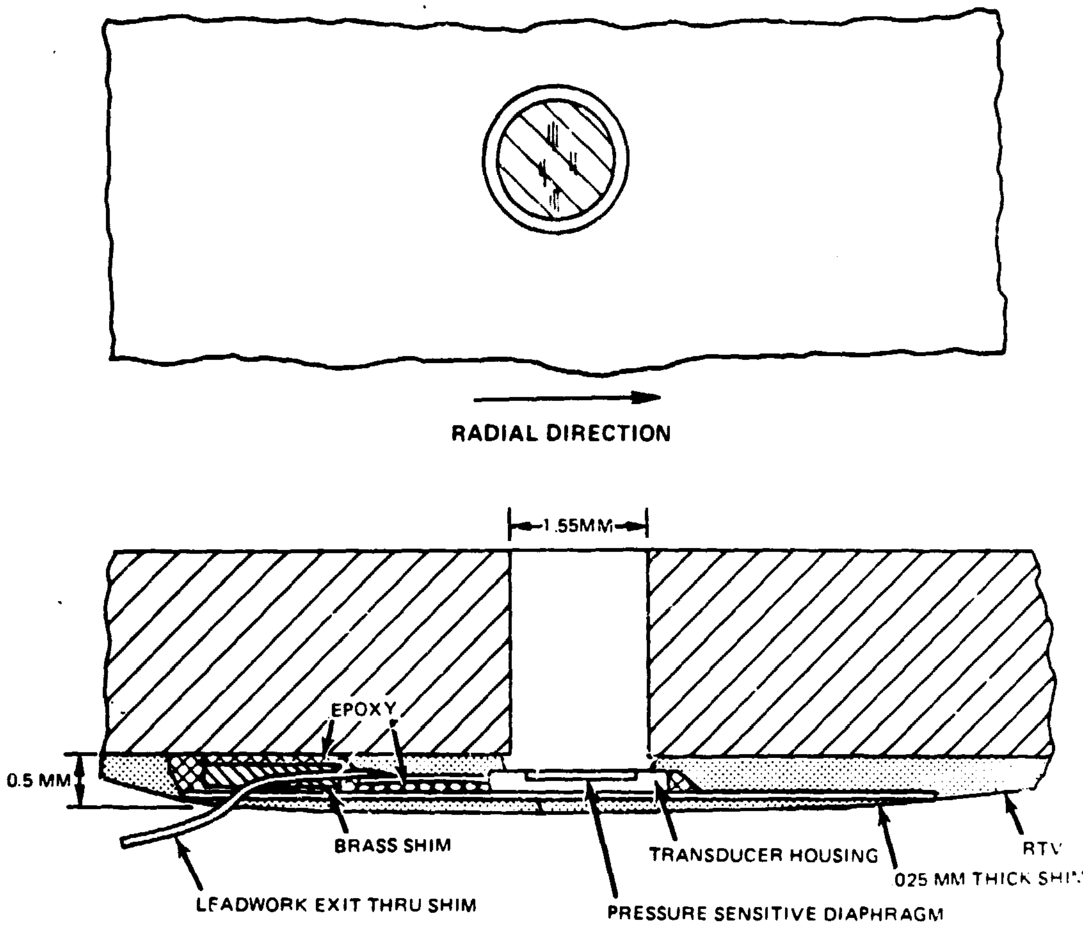
Figure 1a. - Transducer mounting configurations.





CONFIGURATION A'

Figure 1b. - Continued.



CONFIGURATION B

Figure 1c. - Concluded.

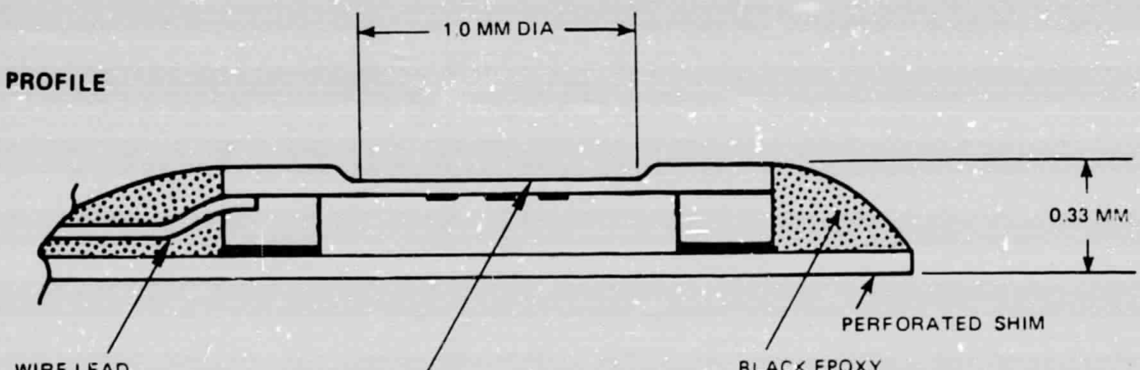


Figure 2. - Pressure transducer.

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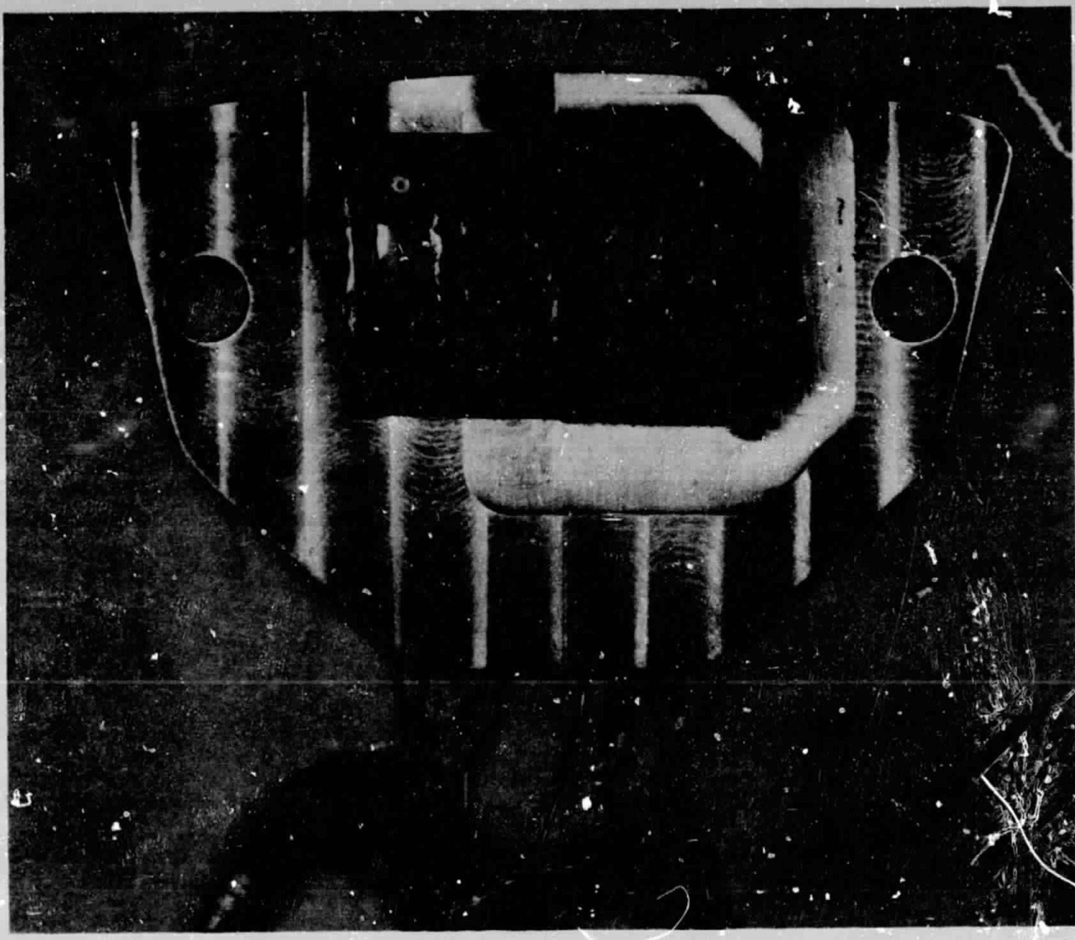

Figure 3. - Instrumented rotating test package.

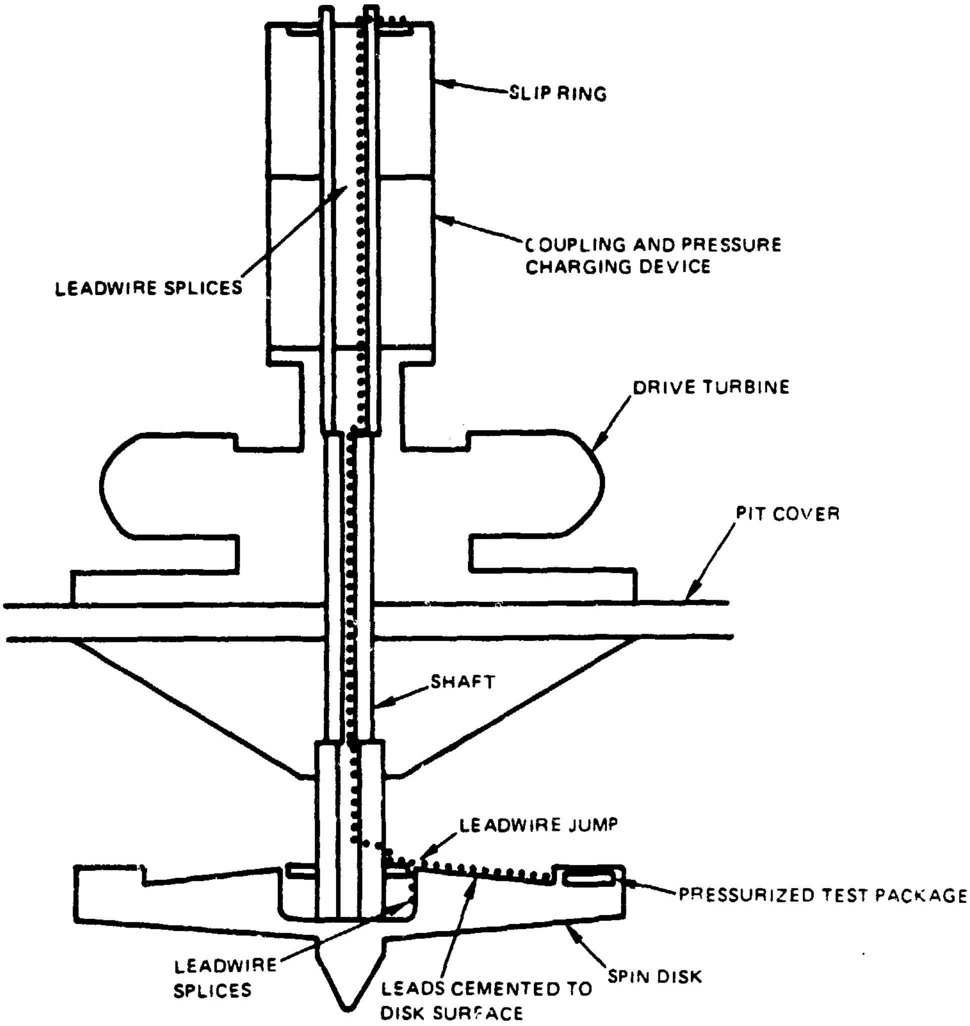

Figure 4. - Rotating test setup.

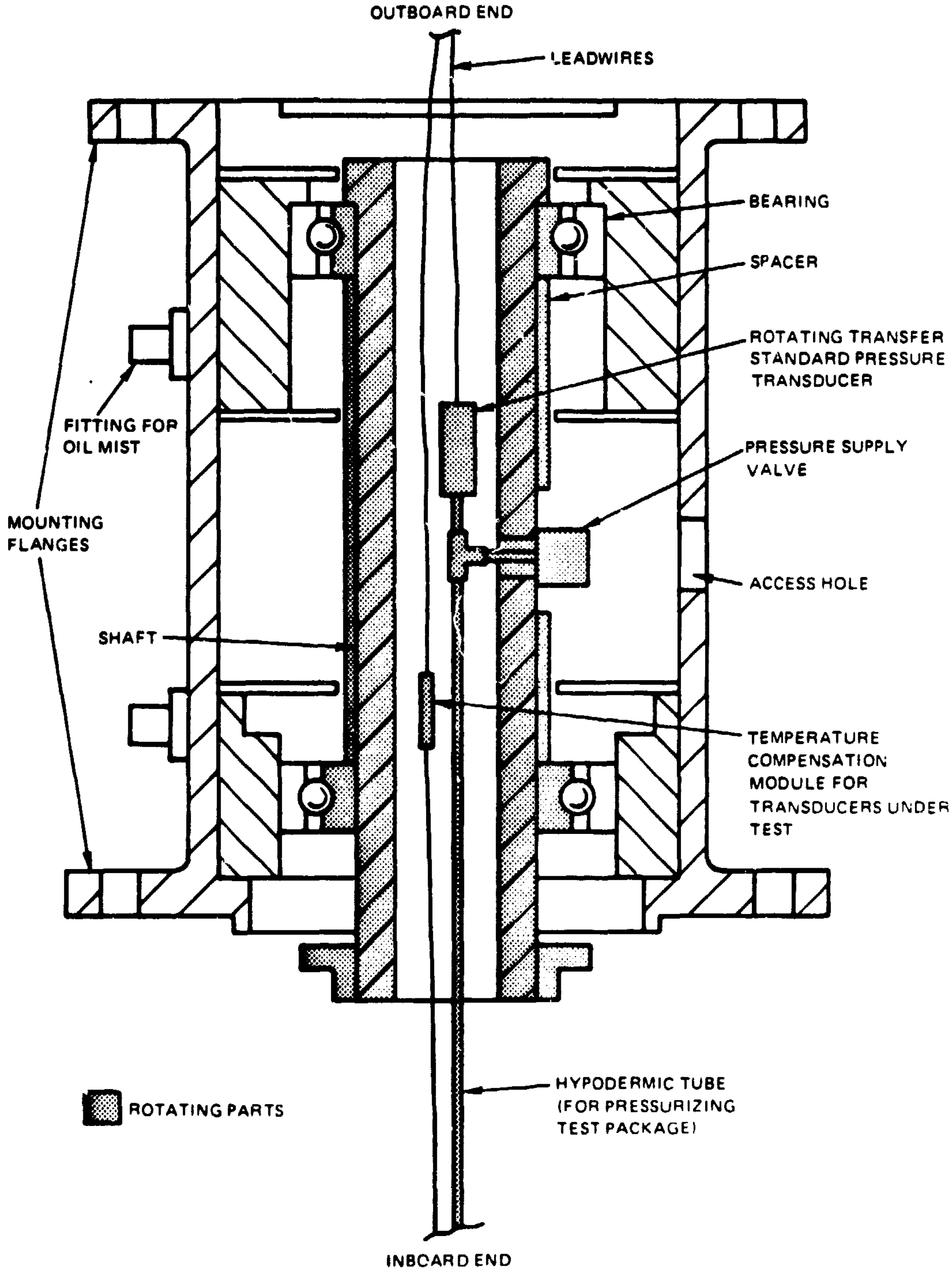

Figure 5. - Pressure coupling assembly.

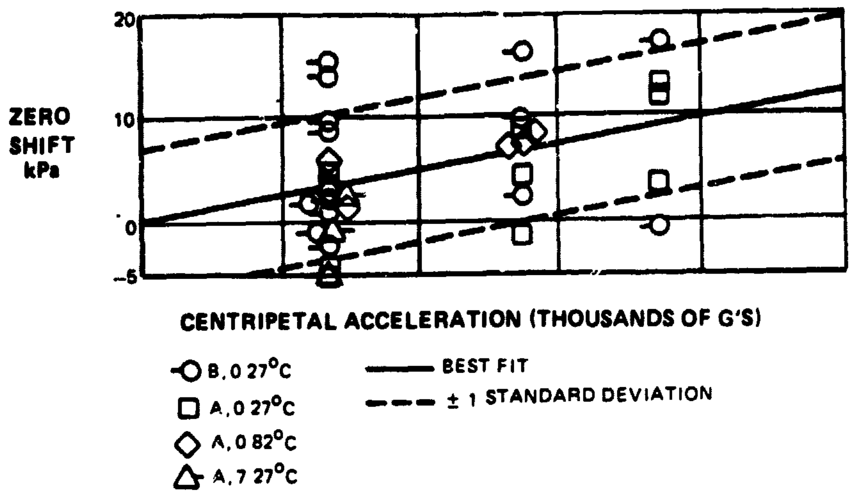

Figure 6. - Effect of centripetal acceleration on zero shift.

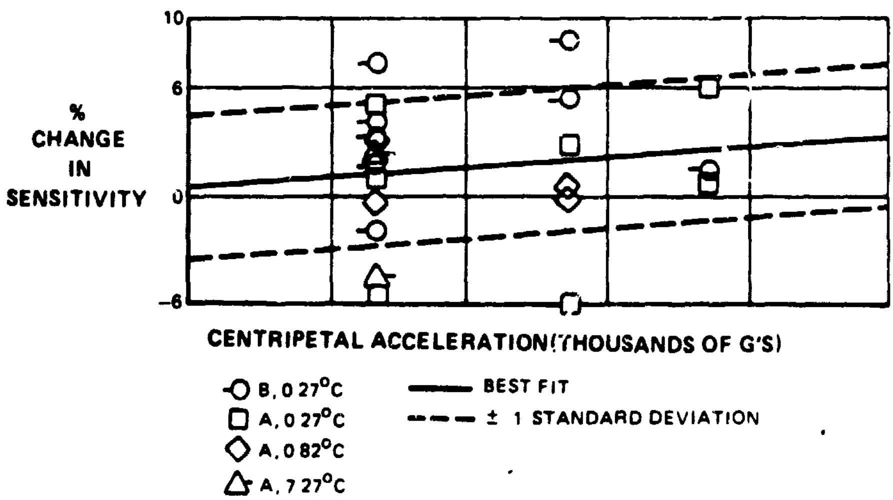

Figure 7. - Effect of centripetal acceleration on sensitivity.

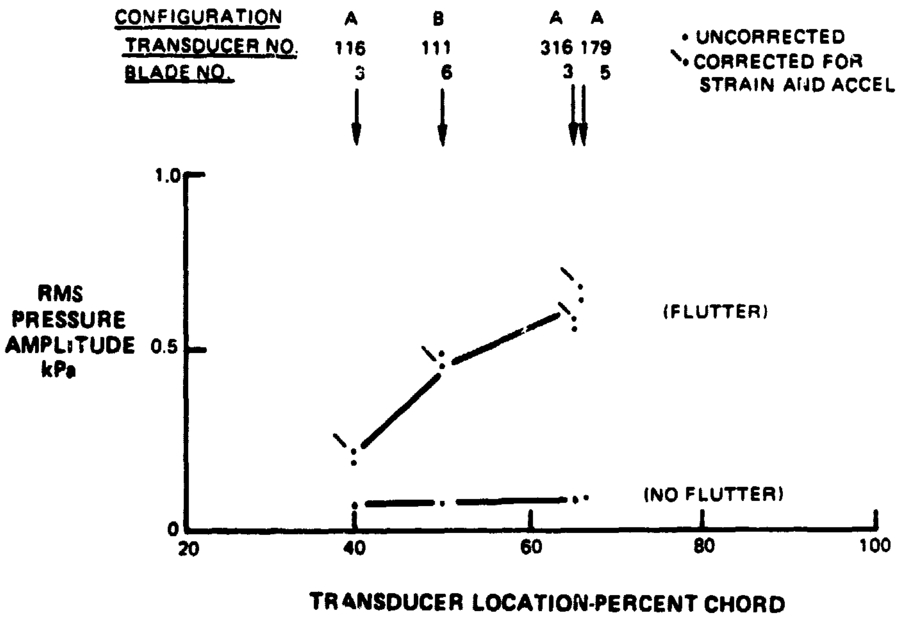

Figure 8. - Surface pressure fluctuation amplitude (KPa rms) versus chordwise position on convex side of TS22 fan blade at 7200 rpm.